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120 Gbit/s Multi-channel THz Wireless Transmission and THz Receiver Performance Analysis

Shi Jia, Xianbin Yu*, *Senior Member, IEEE*, Hao Hu, Jinlong Yu, Toshio Morioka, *Fellow, OSA*, Peter U. Jepsen, and Leif K. Oxenløwe

Abstract—A photonic multi-channel terahertz (THz) wireless transmission system in the 350-475 GHz band is experimentally demonstrated. The employment of six THz carriers modulated with 10 Gbaud Nyquist quadrature phase-shift keying (QPSK) baseband signal per carrier results in an overall capacity of up to 120 Gbit/s. The THz carriers with high-frequency stability and low phase noise, are generated based on photonic photo-mixing of 25 GHz spaced six optical tones and a single optical local oscillator (LO) derived from a same optical frequency comb (OFC) in an ultra-broadband uni-travelling carrier photodiode (UTC-PD). The bit-error-rate (BER) performance below the hard decision forward error correction (HD-FEC) threshold of 3.8×10^{-3} for all the channels is successfully achieved after wireless delivery. Furthermore, we also investigate the influence of the harmonic spurs in a THz receiver on the performance of transmission system, and the experimental results suggest more than 30 dB spur suppression ratio (SSR) in down-converted intermediate frequency (IF) signals for obtaining less than 1 dB interference.

Index Terms—THz photonics, THz wireless communication, uni-travelling carrier photodiode (UTC-PD).

I. INTRODUCTION

ACCORDING to the Edholm's law of bandwidth, the demand of bandwidth to serve both of the increasing wireline and wireless communication data rates is growing every year [1], as represented in Fig. 1. The optical fiber-wireless seamless networks, where data signals are delivered through optical fiber cables and air without any changes to the modulation formats and data rates, will serve as the key building block to support the next generation network for the bandwidth-hungry applications [2]. However, Fig. 1 illustrates that wireless links require further development to keep up with the capacity in the

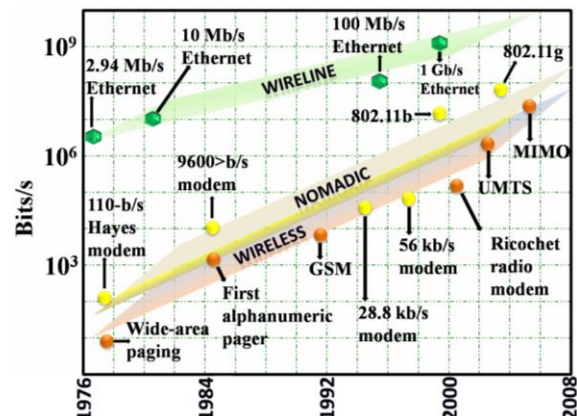


Fig. 1 The increase of data rates for wireless, nomadic and wireline communication technologies against time [1].

optical fiber communication parts, in order to realize seamless integration [3]–[6].

Since nowadays almost all the radio bands in the micro-wave and millimeter-wave regions below 60 GHz have been saturated, the wireless delivery over higher frequency bands has attracted great interest in recent years [7]–[10]. Several systems based on free-running lasers have been reported below 300 GHz frequency bands, such as 75 Gbit/s multi-channel data transmission at 200 GHz [11] and 8 Gbit/s wireless transmission at 250 GHz [12]. In these approaches, since the frequency spacing of two lasers and their phases fluctuate independently, phase noise correction process at reception is needed in the digital signal processing (DSP), which consequently increases the processing time and complexity. On the other hand, optical frequency comb (OFC)-based carrier generation has been investigated in a 100 Gbit/s multi-carrier 200 GHz wireless transmission system [13] and a 100 Gbit/s photonic wireless transmission system operating at 237 GHz [14]. To accommodate the target of well beyond 100 Gbit/s, eventually Tbit/s data rates, frequency bands above 300 GHz are considered to be able to promise an unprecedented capacity, since an extremely large unregulated bandwidth is available in the THz region (300 GHz–10 THz) [15]–[19]. Up to date, the fastest reported wireless system in the THz frequency range (above 300 GHz) is 60 Gbit/s quadrature phase shift keying (QPSK) wireless transmission with real-time capable detection in 400 GHz band [15]. However, the influence of THz receiver imperfect response on the performance of overall system has not yet analyzed in the demonstrations mentioned above.

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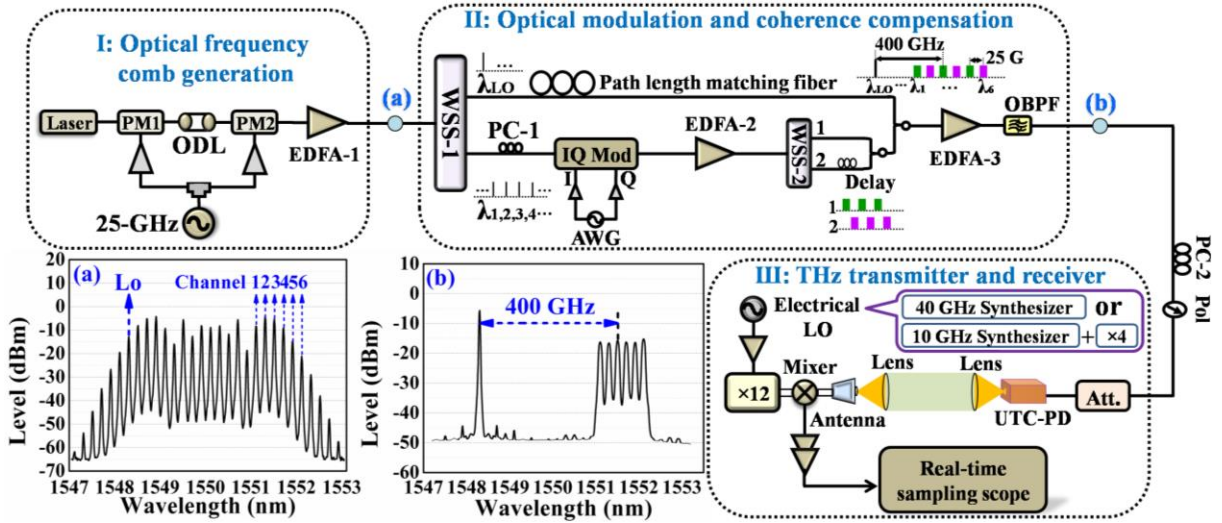


Fig. 2 Experimental setup of multi-channel THz communication system. PM: phase modulator, ODL: optical delay line, EDFA: Erbium-doped fiber amplifier, WSS: wavelength selectable switch, PC: polarization controller, AWG: arbitrary waveform generator, IQ Mod: in-phase and quadrature modulator, OBPF: optical band pass filter, LO: local oscillator, Pol: Polarizer, Att.: attenuator, UTC-PD: uni-travelling carrier photodiode. (a) Optical spectrum of generated frequency comb. (b) The combined spectrum of optical tones launching into the UTC-PD for photo-mixing generation of THz signals.

In this letter, a multi-channel THz wireless communication system in the 350-475 GHz band is proposed and experimentally demonstrated, with frequency division multiplexed six carriers modulated with 10-Gbaud Nyquist QPSK baseband signal per carrier, reaching an overall capacity up to 120 Gbit/s. The THz carriers with high-frequency stability and low phase noise, are generated by photonic heterodyne mixing of optical coherent wavelengths from an OFC. We use an ultra-broadband uni-travelling carrier photodiode (UTC-PD) as the photo-mixing emitter and a Schottky mixer as the electrical receiver to explore large bandwidth in the THz region for enabling such a high capacity. The bit error rate (BER) of the QPSK signal in each channel after wireless delivery is below the hard decision forward error correction (HD-FEC) limit threshold of 3.8×10^{-3} . Furthermore, the influence of harmonic spurs in the THz receiver on the system performance is experimentally analyzed.

II. EXPERIMENTAL SETUP

As shown in Fig. 2, the experimental configuration is mainly composed of 3 sections. Section I illustrates generation of an optical frequency comb. Section II presents optical modulation with Nyquist QPSK signals and phase de-correlation compensation between a single-tone optical local oscillator (LO) and 6 optical tones with modulation. Section III describes the THz link, basically consisting of a UTC-PD as the photo-mixer at transmitter, a 0.5 m THz free-space link and a Schottky mixer as the electrical receiver. Firstly, a 1550 nm continuous wave (CW) laser with a linewidth of 100 kHz, is employed to coherently generate the OFC by simultaneously modulating an amplified 25 GHz sinusoidal radio frequency (RF) signal at two cascaded phase modulators (PMs). Here, an optical delay line (ODL) is used in-between to optimize the delay and to achieve timing match of the two PMs, in order to

broaden the optical spectrum of the OFC for the desired THz frequency signals generation in the 350-475 GHz band.

After an Erbium-doped fiber amplifier (EDFA-1), a wavelength selective switch (WSS-1, Finisar 4000S) is used to select two groups of comb lines spaced at 375-450 GHz and output them from two different ports. One optical tone from one port is used as the optical LO for heterodyne generation of THz signals. A group of six equalized optical tones from the other port is fed into an in-phase (I) and quadrature (Q) modulator, and modulated with a 10-Gbaud Nyquist-QPSK baseband data generated from an arbitrary waveform generator (AWG). After optical modulation and amplification by the EDFA-2, these six optical tones are selectively separated into the even- and odd-order channels by the WSS-2. Here an additional 1 m fiber is placed in the even-order channel path, in order to de-correlate adjacent channels. Then the even- and odd-order channels are combined together with the un-modulated optical LO via two optical couplers. It is noted that a length-matched fiber is added in the optical LO path, in order to compensate the optical phase de-correlation caused by the path difference between the LO tone and the six modulation tones [20]. The path difference is accurately compensated when the lowest phase noise is obtained for the photo-mixed analogue THz carriers [21]. The combined optical signals are then amplified with the EDFA-3 and filtered with a 9 nm optical band-pass filter (OBPF) to reject out-of-band amplified spontaneous emission (ASE).

In the photo-mixing process before the THz link, the beating of the optical LO with the modulated optical tones in a bow-tie antenna integrated UTC-PD [7] generates and radiates multi-channel THz signals in the 350-475 GHz band, also spaced by 25 GHz. Here the incident power of the optical LO is equal to the total power of the six modulated channels, and meanwhile a polarization controller (PC) and a polarizer are used before the UTC-PD, to maximize the polarization dependent optoelectronic conversion efficiency.

The optical power launched into the UTC-PD is controlled by a variable optical attenuator (VOA). Within the 50 cm wireless transmission path, a pair of THz lenses is employed to collimate the THz beam. Subsequently, the received multi-channel THz signals after wireless propagation are individually down-converted into microwave intermediate frequency (IF) for demodulation by using a Schottky mixer followed by a 12-order harmonic electronic multiplier. In order to down-convert the THz signals into the 40 GHz IF domain, the RF LO is in the 28.6-40 GHz range. In our experiment, the RF LO is derived either directly from a 40 GHz synthesizer, or from a 10 GHz synthesizer with 4-time frequency multiplication. Finally the down-converted IF signal is amplified by two cascaded RF amplifiers with total gain of 42 dB, and then sent to a broadband sampling oscilloscope (Keysight DSOZ634A Infiniium) for implementing analog-to-digital conversion, as well as offline second heterodyne down-conversion/data demodulation in the digital domain. The sampling rate and bandwidth of the oscilloscope are 160 GSamples/s and 63 GHz, respectively.

III. RESULTS AND DISCUSSIONS

The spectrum of the generated 25 GHz spaced OFC at point (a) is shown in Fig. 2(a), where the tones labelled by blue arrows correspond to the desired optical LO and 6 lines for optical modulation. As illustrated in Fig. 2(b), the combined spectrum at point (b) consists of one un-modulated LO tone and six wavelength division multiplexing (WDM) tones. Each of six tones is modulated with 10-Gbaud Nyquist-QPSK baseband signals, resulting in an overall capacity of 120 Gbit/s. These 7 tones are launched into the UTC-PD for photo-mixing generation of the 6-channel THz signals at 350 GHz, 375 GHz, 400 GHz, 425 GHz, 450 GHz and 475 GHz, respectively. The combined 6-channel electrical spectrum is shown in Fig. 3(a), which is investigated by measuring the down-converted IF spectrum after wireless delivery. The blue circles in Fig. 3(a) indicate the trends of the received electrical power and signal-noise-ratio (SNR) variation among channels, which is mainly caused by the frequency response of the UTC-PD, wireless channel as well as the THz receiver. Therefore, the frequency response of the whole THz link is also reflected in the measured electrical spectrum. We can observe that the 400 GHz and 425 GHz channels suffer the least link loss among them, 350- and 475 GHz the most, and 375- and 450 GHz in-between. Here, the arrangement of equal channel spacing is to avoid the spectral overlapping after electrical down-conversion. The spectral efficiency can be further increased by using more advanced modulation formats (e.g. 16-QAM) and reducing the number of the guard bands, for example by grouping channels in pairs. Moreover, the employment of the path-length matching fiber results in high frequency stability and low phase noise of the generated THz carriers [20], which benefits the reception.

We have also measured the bit-error-rate (BER) for analyzing the THz receiver performance when driving the THz mixer with and without harmonic spurs. The comparison is realized by using either a 40 GHz high frequency synthesizer as

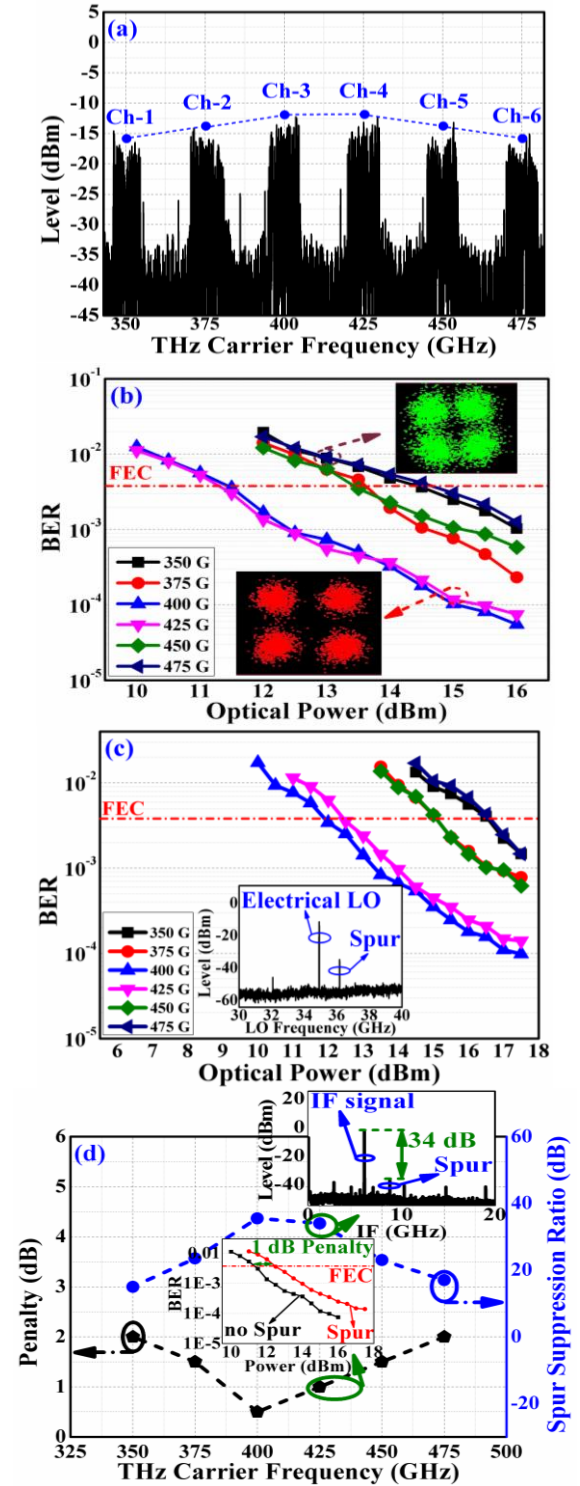


Fig. 3 (a) The combined electrical spectrum of the received multi-channel THz signals with modulation at reception. (b) The BER performance for 6 channels after 0.5 cm wireless delivery without harmonic spurs in the THz receiver. (c) The BER performance for 6 channels after 0.5 cm wireless delivery with harmonic spurs in the THz receiver. (d) The power penalties between (b) and (c) when considering the BER of 3.8×10^{-3} for each channel, and the spur suppression ratio for IF signals in each channel in the THz receiver.

the electrical LO (no spur), or a 10 GHz synthesizer combining the 4-time frequency multiplier as the electrical LO (with spurs) for the mixer. When no spur exists in the receiver, the measured BER performance for all the channels is shown in Fig. 3(b),

where two constellations corresponding to the BER of 1.2×10^{-4} and 9.1×10^{-3} are also exhibited. The BER in the experiment is evaluated from the error-vector magnitude (EVM) of the processed constellations. It can be seen that the BER performance for all the channels is below the HD-FEC limit threshold of 3.8×10^{-3} with 7% overhead FEC code [22], and the power penalty reaching the FEC performance between the best (400 and 425 GHz) and the worst (350 and 475 GHz) channels is around 3 dB. This penalty can be explained by the un-even frequency response of the whole THz link shown in Fig. 3(a), which complies well with the BER performance observation.

When harmonic spurs exist, the measured BER results of 6 channels are shown in Fig. 3(c). Here the electronic spurs originating from the 4-time frequency multiplier are also displayed. It can be seen that the BER performance trends of these 6 channels also complies with the frequency response of THz link in Fig. 3(a). Besides that, it is noted that the penalties between those in Fig. 3(b) and (c) at the BER of 3.8×10^{-3} are about 2 dB for the 350 GHz channel, 1.5 dB for 375 GHz, 0.5 dB for 400 GHz, 1 dB for 425 GHz, 1.5 dB for 450 GHz and 2 dB for 475 GHz, respectively, as shown in Fig. 3(d). In addition, we measure the spur suppression ratio (SSR) for all the channels to investigate the interference of spurs. Here the SSR is evaluated by measuring the down-converted IF signals without modulation, and the results are displayed in Fig. 3(d). We can see from Fig. 3(d) that when the SSR is higher than 30 dB, the induced penalty is less than 1 dB, but the penalty increases to 2 dB when the SSR level decreases to 15 dB. As an illustration, the measured BER performance and electrical spectrum in the IF region of the 425 GHz channel are displayed in Fig. 3(d), for analyzing the BER penalty and the SSR.

IV. CONCLUSION

We propose and experimentally demonstrate a 6-channel THz wireless communication system in the 350–475 GHz band with a link capacity of up to 120 Gbit/s. The performance of Schottky mixer-based THz receiver for detecting multi-channel THz signals is also investigated. The experimental results validate that the existence of harmonic spurs in the receiver with a SSR less than 20 dB within the demodulation bandwidth will significantly affect the overall system performance, and suggests more than 30 dB SSR for obtaining less than 1 dB interference. This work provides the support of further development of high-speed THz wireless communication systems.

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